U.S. DEPARTMENT OF ENERGY

Report on the Status of the Solid Oxide Fuel Cell Program

Report to Congress
August 2019

United States Department of Energy
Washington, DC 20585

Message from the Secretary

This is a report on the status of the Solid Oxide Fuel Cell Program administered by the Department of Energy's Office of Fossil Energy. This Program focuses on research, development, and demonstration activities to enable generation of highly efficient, cost-effective electricity from coal and natural gas with near-zero atmospheric emissions.

In response to the request contained in House Report 115-697, this report is provided to the following Members of Congress:

- **The Honorable Richard Shelby**
  Chair, Senate Committee on Appropriations

- **The Honorable Patrick Leahy**
  Vice Chairman, Senate Committee on Appropriations

- **The Honorable Lamar Alexander**
  Chairman, Subcommittee on Energy & Water Development
  Senate Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Ranking Member, Subcommittee on Energy & Water Development
  Senate Committee on Appropriations

- **The Honorable Nita M. Lowey**
  Chairwoman, House Committee on Appropriations

- **The Honorable Kay Granger**
  Ranking Member, House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Chairwoman, Subcommittee on Energy and Water Development
  House Committee on Appropriations

- **The Honorable Mike Simpson**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations

If you have any questions or need additional information, please contact Ms. Jazmin Everett, Congressional Liaison, Office of the Chief Financial Officer, at (202) 586-2499.

Sincerely,

Rick Perry

Rick Perry

Executive Summary

The Office of Fossil Energy has prepared this report in response to a request from the United States Congress to provide a summary of the status of the Office of Fossil Energy's Solid Oxide Fuel Cell (SOFC) Program (Program). A SOFC is an electrochemical device that produces electricity directly from the oxidation of a hydrocarbon fuel, while eliminating the actual combustion step. It has inherent efficiency advantages not offered by other methods of electricity production. This report summarizes the significant technological advancements toward the Program's goal of commercialization via partnerships with National Laboratories, academic institutions, and industrial partners.

The Program has identified several key technology areas that affect the performance of a SOFC: core technology, cell development, and system development. The Program operates on two parallel paths to investigate these technology areas: 1) early stage research and development (R&D), which includes core technology and part of cell development and 2) research, development, and demonstration (RD&D), which includes the balance of cell development and system development. Many SOFC projects have aspects that fall into more than one of the key technology areas. Laboratories within universities or within the National Laboratory system generally perform the solely R&D projects, while commercial entities perform the solely RD&D projects. Because RD&D projects need to purchase expensive equipment and materials, they are usually more costly than R&D projects.

This report identifies areas that need continued work. The results indicate the need to locate suitable replacement materials for high-temperature operations and for extending operating lifetimes. The Program should continue supporting the commercialization of smaller-scale devices through projects within the SOFC community, while simultaneously supporting efforts to develop systems of one megawatt or higher capacity. The Program is taking early steps to use a SOFC to capture the abundant energy available from coal via coupling with a gasifier. These steps should continue to be expanded.

There has been progress towards the goal of practical and sustainable solid oxide fuel cells, but the RD&D has yet to reach the developmental tipping point required to incentivize industry to continue RD&D without Federal support.

REPORT ON THE STATUS OF THE SOLID OXIDE FUEL CELL PROGRAM

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I. Legislative Language

This report responds to legislative language set forth in the Energy and Water Development Appropriations Report, 2019 on page 94, wherein it is stated:

> *The Department is directed to provide to the Committees on Appropriations of both Houses of Congress not later than 180 days after the enactment of this Act a report on the status of the Solid Oxide Fuel Cell Program. The report shall include a discussion of the technological achievements of the program, including lessons learned, and a discussion of the technical requirements to achieve the remaining goals of the program.*[1]

The Joint Explanatory Statement of the Committee of Conference for fiscal year (FY) 2019 Appropriations stated the following:

> *This conference report, while repeating some report language for emphasis, does not intend to negate the language and allocations set forth in House Report 115-697 and Senate Report 115-258 and that direction shall be complied with unless specifically addressed to the contrary in the accompanying bill or conference report……In cases where the House or the Senate has directed the submission of a report, such report is to be submitted to the Committees on Appropriations of both Houses of Congress. House or Senate reporting requirements with deadlines prior to or within 15 days of the enactment of this Act shall be submitted not later than 60 days after the enactment of this Act. All other reporting deadlines not changed by this conference report are to be met.*[2]

This report updates the status of the U.S. Department of Energy's (DOE) Solid Oxide Fuel Cell (SOFC) research, development, and demonstration (RD&D) Program since the last report to Congress on this subject submitted in December 2017.

II. SOFC Technology Overview

A fuel cell is an electrochemical cell that directly converts the products of a chemical reaction into an electrical current. While there are many different types and configurations of fuel cells, all fuel cells contain an anode and a cathode separated by an electrolyte. The SOFC cathode catalyzes the conversion of oxygen molecules (typically from air) to the oxygen ions. The electrolyte allows the passage of the oxygen ions from the cathode to the anode but prevents the passage of electrons. At the anode, oxygen ions react electrochemically with the fuel (typically hydrogen) in a reaction that releases electrons to an external circuit and produces

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[1] H.R. Rep. No. 115-697, at 94 (2018).
[2] H.R. Rep. No. 115-929, at 87-88 (2018) (Conf. Rep.).

usable power. Connecting the external path back to the cathode completes the circuit. In contrast to most other fuel cells, SOFCs must operate at high temperatures (typically 800°C or higher). Refer to Appendix A for more information: https://www.energy.gov/fe/downloads/appendix-sofc-primer.

III. Conduct of This Review

To prepare this report, the Program selected a representative portion of past and ongoing SOFC RD&D projects to place within the scope of the review (see Appendix B: https://www.energy.gov/fe/downloads/appendix-b-quick-reference-guide). The Program selected 46 projects that spanned all key technology areas and included investigators from National Laboratories, universities, and industry partners. DOE limited the review to information that could be suitable for release to the public. Information that could not be made publicly available, such as proprietary information or financial details is outside the scope of this report.

Subject Matter Experts

DOE utilized a panel of qualified subject matter experts (SMEs), (refer to Appendix C: https://www.energy.gov/fe/downloads/appendix-c-biographical-information-smes) to conduct the technical review and analysis for the report. The National Science Foundation recommended candidates for the panel, and the Office of Fossil Energy screened the candidates for their qualifications and potential conflicts of interest.

Information Collection and Dissemination

To supply the SMEs with project-specific information, the Program asked Project Managers and Principal Investigators from each of the 46 projects to submit the following documents:

- Statement of Project Objectives (SOPO)
- The Funding Opportunity Announcement (FOA) the performer responded to
- Annual Reports
- Final Report (if applicable).

In practice, no central repository of information for this type of Program review exists. As such, the Program collected supplemental information from a number of public sources, such as:

- **SOFC Program Manager Database**: This informal database created by the SOFC Program Manager provided general information on the projects for review, including award values, start and end dates, and other relevant details.
- **Office of Science and Technology Information website**: This DOE office is responsible for collecting, preserving, and disseminating both unclassified and classified scientific and technical information from DOE-funded research and development (R&D) activities. The

website provided articles describing the results of various projects reviewed during the preparation of this report.

- **National Energy Technology Laboratory website**: This website provided access to project descriptions and project benefits, as well as access to presentations and publications developed by the performer. Many projects produced PowerPoint-style presentations in lieu of formal status reports.
- **Internet searches and other sources**: When project-specific details were not available elsewhere, the Program searched and reviewed other sites, such as individual Performers' public websites.

Organizing SME Feedback

In effort to standardize and collect project-specific data, the Program sent a survey questionnaire to the SMEs (see Appendix D: https://www.energy.gov/fe/downloads/appendix-d-survery-form-and-instructions). The questionnaire asked the SMEs to evaluate whether they agreed or disagreed with each question or statement in the questionnaire and provided space for a written justification. The SMEs had 30 days to conduct the reviews and return the questionnaires for each project assigned.

After the Program received and processed the project-specific questionnaires, it asked the SMEs a second round of questions (see Appendix E: https://www.energy.gov/fe/downloads/appendix-e-follow-questions). These questions focused on the portfolio as whole, not specific projects. The SMEs offered thoughtful responses that, along with the questionnaire responses, formed the basis of many of this report's conclusions.[3]

IV. Status of the SOFC Program

Since its inception in 1995, the SOFC RD&D Program has made progress toward achieving its technical goals, although several developmental challenges remain. The goals of the SOFC RD&D Program are:

- Improve efficiency of SOFCs to 60 percent without incorporating carbon capture and sequestration
- Achieve a proven lifetime of 40,000 hours or more
- Achieve less than 0.2 percent per 1,000 hours of degradation rate
- Decrease the stack costs of SOFCs to less than $225 / kilowatt (kW)
- Decrease system SOFC costs to less than $900 / kW

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[3] The largest challenge to evaluating the SOFC Program was obtaining a representative portion of information. As previously discussed, no one central repository of information on all SOFC projects exists. Limiting the body of reviewable documents to those suitable for public release essentially eliminated all financial data except topline award allocation amounts. Considering financial granularity would have produced addition conclusions.

The SOFC high operating temperature requirement presents challenges that make attaining the Program goals problematic. These challenges include the management of heat and gas flow across the fuel cell stack, reducing the operating temperature (which would increase the operating lifetime), and heat-induced chemistry changes. Other challenges external to the SOFC stack but part of the system include implementing a systems approach when designing a SOFC-based power system; the high cost of materials; difficulty replacing specialty items; and integrating the SOFC stack with the Balance of Plant (BOP) equipment, which includes stack kinetics and load following. These challenges increase the complexity of designing SOFC systems. However, progress in one topic area often influences or complements work in another. For example, efforts to reduce the SOFC operating temperature also could result in reducing the vaporized chromium issue, which is beneficial to the operation of the SOFC.

In addition to these technical challenges, the Program is supporting the development of the gasification and conversion of coal to syngas as a fuel for SOFCs, which would extend the Nation's most abundant fossil energy source. Another challenge is identifying a stable commercial partner willing to work cooperatively with the Program toward the development and commercialization of a SOFC power system in the 1–10 megawatt (MW) range, which is a considerable step up from current designs.

Program Progress Regarding High-Temperature Operation

SOFCs typically operate in the temperature range of 800 – 1000°C (1440–1800°F). This is a harsh, demanding condition; for example, iron glows red at 500°C (900°F). Few low-cost, readily available materials can withstand these temperatures for extended periods. Finding materials that can tolerate these high temperatures improves SOFC durability and lifespan. Various projects made significant achievements in improving the heat/gas flow management in the high–temperature regime, such as:

- One project evaluated and tested a high–temperature ceramic heat exchanger, which demonstrated a significant technical achievement in the control of heat/gas flow management systems. A heat exchanger was developed using alumina and alumina-silicate materials instead of chromium-containing metals. By using alumina and alumina-silicate materials, efficiency rose to 76 percent, which exceeded the 73 percent target efficiency rate and proved that a design to minimize chromium poisoning in the SOFC could also provide the necessary heat more efficiently.
- A second project modeled stack temperature distribution as a function of fuel gas leak rate. This activity led to more reliable designs of seals to control precisely fuel gas leakage. This project also considered the integration of a radial heat reformer to improve heat flow management.
- A third project developed an anode blower integrated with other module components in the modular power block. The blower failed during testing, but the results of the failure and the reporting that followed provided valuable data for improving the latest generation of anode blowers.

Program Progress on Extending Operating Lifetime

No SOFCs in the portfolio have achieved a proven lifetime of 40,000 hours or more with less than 0.2 percent per 1,000 hours of degradation rate. However, certain components have been tested for that duration. One project utilized the strontium nickel oxide getter[4] for chromium, which survived 40,000 hours of operation with less than 0.2 percent per 1,000 hours of degradation rate. All SMEs agreed that this is a critical goal to commercializing SOFCs and ensuring they are competitive with other electricity-generation technologies. SMEs agreed that more study and testing are needed to understand fully what technical barriers to this goal exist, but no SMEs suggested that this goal is unreasonable or unattainable.

Degradation Rate Less than 0.2 Percent per 1,000 Hours

Reducing the degradation rate is corollary to extending the operating lifetime. Within the portfolio, there are several examples of projects that demonstrated results in lowering the degradation rate on the same order of magnitude of the goal:

- One project reported a broad spread in degradation rates, ranging from 0.2 percent to 1.6 percent per 1,000 hours under realistic operating conditions.
- Another project developed a hetero-structured cathode with interstitial oxygen defects onto nickelate/lanthanum strontium cobalt ferrite that enhanced the cathodic oxygen reduction reaction. This project reported achieving a degradation rate of 0.39 percent after 500 hours at 710oC.
- One project identified that cell defects and inhibition of poisons from material and the operating environment and material changes over time (e.g., due to oxidation/reduction reactions) are technical hurdles that could preclude achieving a degradation rate of less than 0.2 percent per 1,000 hours.

Operating Lifetime Greater than 40,000 Hours

The Program has two projects with commercial partners that examine SOFC power systems in the 200 kW or greater range to test long-term operability. The following projects have demonstrated the challenges of long-term operability:

- LG Fuel Cell Systems (LG) designed, fabricated, and operated a 250 kW SOFC system that was located in Canton, Ohio, and connected to a local grid. This system operated approximately 1,800 hours with more than 1,200 hours in continuous operation. Based on corporate business decisions, LG has terminated this project and departed the field.
- Fuel Cell Energy designed and fabricated a 200 kW SOFC system. This unit is located on-site in Pittsburgh, Pennsylvania. It passed all of its pre-operational tests and placed in its normal operation mode on April 9, 2019. This system is set to run continuously to test long-term operability of their SOFC system.

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[4] A getter is a deposit of reactive material that absorbs or reacts with select chemical species in the air to remove them from the system.

Progress on Managing Chemical Changes during Operation

The high operating temperature of a SOFC is necessary for both the electrode (anode and cathode) for higher kinetics and the electrolyte for higher oxygen ion conductivity. The high operating temperature has other chemical effects on the operation of the SOFC. For example, the high temperatures cause the vaporization of chromium oxide from stainless steel components, which then acts as a catalytic poison on the cathode. The high temperatures can dislocate the strontium in the SOFC matrix, and cause grain-size enlargement, which reduces electrochemical reaction sites. The Program has made progress in overcoming these challenges through the following projects:

- One project advanced the development of new getters with improved tolerance to chromium. This project demonstrated a system-wide improvement and provided data on how to utilize the getter more effectively.
- Another project advanced the development and design of a specialty sensor utilizing a solid electrolyte to detect chromium vapors with and without interfering oxygen. The project demonstrated that two different materials (yttrium-stabilized zirconia and Beta-alumina) can be used at high operating temperatures, but both materials should react with chrome species to change the electrical conductivity of the solid state for detection.
- A separate project evaluated whether different grades of alumina-forming austenitic alloys are better candidates for BOP components that avoid or minimize chromium release. While these alternative materials can minimize the release of chromium, when compared with stainless steels, there may be increase of creep and a lower corrosion resistance. Another project uses aluminide coatings to cover chromium-containing steels, which can improve the overall BOP component oxidation. Tests using the investigators' commercial AlumiLok® coating showed improvements in performance of enhanced high-temperature oxidation, chromium volatilization, and coking/carburization resistance.

Program Progress on Integrating with Balance of Plant Equipment

BOP equipment includes all devices needed to deliver fuel and oxygen (air) to the SOFC and to remove exhaust gases as well as perform any necessary fuel reforming. BOP equipment also includes equipment needed for cell temperature maintenance, electrical output collection, and the conversion of direct current to alternating current with an inverter. The Program has made progress in integrating with BOP equipment through the following projects:

- The development and design of a "compact stack architecture" produced an 80 percent savings in cost of materials, mainly through reductions in repeat non-cell components and non-repeat components. This design integrated the hotbox in its BOP design.[5]
- A key BOP issue is chromium vapor, where the volatilization of chromium from components that contain elemental chromium makes its way to the SOFC stack and degrades the

[5] A hotbox unit integrates the high-temperature components of a SOFC, including the reformer and afterburner, into a single unit to facilitate system integration and reduce cost.

cathode performance. One project is exploring a strategy to reduce the poisoning effect of chromium on the cathode by eliminating chromium from the BOP in the first place.

- Two projects worked to reduce the chromium vapor by sequestrating chromium utilizing newly developed getters to trap the chromium before it harms SOFC performance. Both projects investigated the reactive transport of chromium within lanthanum strontium manganite cathodes under variably humid environments.
- One project worked to develop a getter for chromium using different strontium nickel oxide materials prepared by different methods. The project characterized and tested them under cell operating conditions. The test results showed evidence of chromium capture. Design studies were performed for 40,000 hours of the getters' lifespan. The investigators examined different processing methods and found that a new chromium getter showed no phase changes and did not interact with humidity and carbon dioxide present in air.

Program Progress on Reducing the Cost of Materials

Multiple projects within the portfolio focus on reducing the cost of the materials within SOFC development. Program funding allowed the following technical achievements associated with reducing the cost of materials:

- The design and development of new infiltrated cathodes and anodes produced a 30 percent reduction in the cost of materials in one project. The design also included a new silver current collector that contributed to the reduction in cost of materials.
- The design and development of an alkali-free barium borosilicate glass exhibited improved performance. Although the exact cost savings were not provided, SMEs determined that this would reduce material costs moving forward.
- The design and development of low-cost lanthanum strontium cobalt ferrite (LSCF) cathodes demonstrated improved activity and performance.
- The development of a better variation of the low-cost cathode performed superiorly when used together with a nanoscale praseodymium-ceria barrier layer.[6]
- The demonstration of a scalable 5 kW SOFC power system utilizing a novel lower-temperature (~600^{o} C) ceria electrolyte demonstrated a cost reduction for other SOFC components' materials.
- One project analyzed the cost and performance of sinterable materials when used as "cathode-side" contacts. The performance of low-cost, earth-abundant oxides was compared against slightly higher-cost alloy nickel-iron oxide powders.

[6] There is a cost trade-off for this variation. Praseodymium oxide is roughly 3,000 times more expensive than yttrium used in the yttrium-stabilized zirconia (YSZ) electrolyte, and 13 times the cost of ceria, another common barrier layer within the SOFC, but the small amount of praseodymium oxide needed may partially outweigh this cost difference.

Program Progress on Replacing Specialty Items

SMEs noted the following example as significant technical achievements regarding the development and use of specialty items necessary for SOFC power generation:

- One project advanced the development of a multivariable gas sensor for use at high temperatures applying an optical approach. The optical approach can inherently result in longer-lasting sensors combined with gas discrimination. Multiple independent responses from an individual sensor provide selectivity of detection in gas mixtures. The design is based on nano-structuring the device surface to provide controlled extinction and scattering of light. Operation requires gas adsorption, and re-use of the sensor would require desorption. The project documented its use over many days, and the sensor demonstrated a tenfold increase in sensitivity over the conventional sensor. Tests with different hydrogen-to-carbon monoxide ratios also clearly indicated selectivity of the new gas sensor.

Program Progress on Load Following and Cycle Stability

The main advance in this area was the development of barrier layers to control strontium segregation in LSCF cathodes and anode treatments to enable operation in high humidity (high fuel utilization) conditions. Other achievements include:

- The development of a thinner anode substrate enabled operation beyond 85 percent fuel utilization (high humidity operation) and increased performance with reduction in anode porosity.
- The detailed characterization of inter-diffusion and mitigation of inter-diffusion in SOFC cathodes reduced the inter-diffusion in gadolinium-doped ceria and YSZ, leading to improved kinetics for oxygen reduction.
- Exploration and description of the use of praseodymium- and neodymium-nickelate-doped mixed ionic and electronic conductors as dense barrier layers for LSCF cathodes reduced strontium segregation.
- The examination of nickel-infiltrated lanthanum-strontium-nickel-cobalt and nickel/YSZ anodes achieved improved performance (current density at given voltage) between 35 and 60 percent. The performer also noted better stability in high humidity environments. This observation will lead to further long-term stability studies with the anode infiltration.
- The development of cylindrical SOFCs improved performance in the temperature range of 650°–700°C. The improved performance was due to infiltrated cathodes (7 percent improvement) and infiltrated anodes (10 percent improvement). These improvements enabled operation at lower oxygen-to-carbon ratios for improved resistance to coking. This project also examined an integrated iron fuel element that protects the nickel anode from oxidation.
- One project focused on the development and production of a materials database to assist future research in SOFC electrode materials. The project also developed a SOFC multi-physics software package for two-dimensional and three-dimensional modeling of single cell behavior.

- Another project developed a prototype stack test unit, which enabled stack testing or simulation based on measurements of a single cell.
- A change in the lattice parameter induced by electric potentials for LSCF cathodes provided information related to the mechanism of the oxygen ion transport. This mechanism is a fundamental step of SOFC operation.

Program Progress on Using Syngas as the Fuel

One of the ultimate goals of the Program is the development of a SOFC system powered by the Nation's most abundant fossil energy source: coal. This requires that a coal gasifier be in close proximity to the SOFC so the gasifier output fuels the SOFC. The University of North Dakota Energy & Environmental Research Center has conducted extensive coal gasification research and has entered into an agreement with DOE to expand the test center to investigate the performance of SOFCs (single cell or stack) when the fueled by syngas from their test gasification units. This effort began in January 2019 and will provide insights on the linkage between a highly efficient power generator and a readily available fuel source.

Program Progress on Finding a Commercial Partner

The Program actively seeks a commercial entity to work cooperatively on the design, fabrication, testing, and commercialization of a 1–10 MW SOFC power system. Systems of this capacity are a considerable step up from current designs. However, a 1 MW system could be developed by combining ten 100 kW modules, which is within current capabilities. Such a project would be very expensive. With the shutdown of the LG Fuel Cell Systems projects and the departure of four other major corporations since 2012 due to a variety of reasons which have not been made public, companies who could be joining in a project for a larger system appear to be taking a "wait and see" attitude toward the development of larger SOFC systems.

V. Lessons Learned

Both the public and private sectors benefit from working together on SOFC development. The public sector gains a cost-effective and efficient method of fulfilling its mission to help the Nation develop clean and affordable energy from domestic fuel resources. The private sector gains access to funding and academic research that incentivizes market entry.

As the Technical Readiness Levels (TRLs), (see Appendix F: https://www.energy.gov/fe/downloads/appendix-f-trl-guide) have increased towards commercialization and DOE has prioritized early-stage research, there is evidence of a potential divergence of focus, interests, priority, and risk tolerance between DOE, university partners, and industry partners. As technologies proceed up the TRL scale and develop greater technical maturity, awardees become less willing to share system developmental and operational information where a competitor in the eventual marketplace may use such knowledge.

VI. Recommendations

While DOE believes that fuel cells have a role in achieving the Nation's clean energy goals, the current state of SOFCs requires additional early-stage applied and basic R&D to mature the technology. Based on the results presented in this report, the Program has identified the following gaps and technical needs:

Existing Validation and Design of Commercial SOFC Systems

Any new technology needs to be demonstrated at a scale that provides an accurate prediction of its performance during commercial operation. The following ongoing activities for field testing and commercial design of larger SOFC systems will help to identify applied R&D needs.

> <u>Validating SOFC Systems Performance at Small Pilot Scale</u>
> The Department has supported the development of a 200 kW SOFC that is currently undergoing testing with the purpose of achieving a minimum of 5,000 hours (seven months) of continuous operation. We believe that this test will provide a significant amount of information that will help evaluate the future role of early-stage/basic R&D. The vendor should expand the test program to at least 8,000 hours (one year) of unattended, continuous operation to demonstrate the robustness of the system. The longer-term test will demonstrate that the vendor has the ability to bring a credible product to the market place.
>
> <u>Demonstration and Development of Megawatt and Larger SOFC systems</u>
> The Department is performing a front-end engineering design (FEED) study to design a 1,000+ kilowatt-electric (kWe), or 1 megawatt-electric (MWe), SOFC system to establish the costs and technology gaps preventing the development of systems this size. This study should provide valuable information to shape future early-stage R&D in SOFC.

Continued Funding of Early-Stage Applied R&D

While the Program emphasizes the development of commercial products, it also supports the development of new and innovative ideas in materials, process design, and system optimization. Understanding high-temperature operations and system performance with materials degradation is fundamental to understanding material performance and novel concepts that keep the Program on the leading edge of SOFC technology. The Program should continue supporting basic R&D at the early stages (TRLs 2–4: simulation, laboratory, and bench-scale R&D) to solve the following fundamental issues:

> <u>Effects of High-Temperature Operations on Materials Degradation</u>
> The Program investigates the impact of high operating temperatures on the performance of SOFCs. These temperatures are required to achieve high efficiencies, but they also have several undesirable side effects: performance degradation, chromium vaporization, grain enlargement, and strontium migration. The Program

should continue working with its industrial partners to find solutions, as these temperatures would be common in industrial applications.

Optimizing Systems Performance–Operating Lifetime Longevity

Small SOFC systems may operate for long durations, but these systems do not produce power on an industrial scale. The Program encourages other industrial SOFC developers to increase the scale of the systems in development to aggregate data on materials and process performance over extended durations. Larger-scale systems with adequate operating lifetimes are necessary to show commercial practicality of SOFCs for industrial sources. The Program should continue to work with its industrial partners to increase operating lifetimes of a system that would support industrial processes.

SOFCs do not operate in isolation. Rather, a variety of specialized equipment supports the SOFC. The Program's support of developers' system integration efforts brings the industries nascent SOFC systems closer to commercialization. These efforts include identifying and developing new materials that have improved chemical and mechanical behavior and developing new cost-effective methods and processes to achieve system goals.

Simulation of Optimized SOFC Systems – Reducing Costs

The costs of SOFC power systems must be competitive with other electricity generation methods. The Program should work with developers across the entire process—from initial concepts to commercialization—to determine how to reduce system and operating costs without sacrificing performance or reliability. The extensive cost-modeling capabilities of the National Energy Technology Laboratory will provide insights on cost management and reduction.

Replacing Specialty Items and Materials (Supply Chain R&D)

Many of an SOFC's support components are specialty items designed specifically for SOFC power systems. Replacing these specialty items with existing, commercially available components is one method in reducing the overall installation costs of a SOFC system. The Program should continue investing in supply chain R&D to identify potential cost-savings. For example, operating SOFCs at lower temperatures could allow the replacement of a specially designed blower with a less-expensive, off-the-shelf item.

Operations on Syngas and Other Coal-Derived Fuels

The Program should support the development of SOFC systems capable of running on syngas or other coal-derived fuels, which are abundant resources. The Program has begun the development of a test center for SOFCs on syngas utilizing the existing coal gasifiers at the University of North Dakota Energy & Environmental Research Center. The Program believes the operation of SOFCs on syngas or other coal-derived fuels is an important step in making these power systems competitive. This work contributes to the success of SOFCs as a commercial product, and as such, all early-stage research on materials and process design should include early-stage testing on coal-derived syngas.

Industry Engagement and Open Source Data

Locating Industrial Partners Willing to Develop Larger-Capacity Systems
Since 2012, five commercial entities have ceased their SOFC system development efforts. The long-term continued success of SOFC power systems depends on identifying and supporting commercial partners that have demonstrated persistence, survivability, and economic commitment to bringing SOFCs to a marketable product. The Program already works with one Company (FuelCell Energy) and should continue its efforts to expand the number of manufacturers capable of supporting SOFCs as a commercial product line.

Sharing of Data
Data availability is a challenge that the Program must overcome to understand fully the progress needed to commercialize SOFC systems. Although technical achievements are observable and well documented within each awarded project, there is a concern that the achievements of each project are not being shared or disseminated to other active projects that may benefit from the findings.

Fundamental SOFC Program Activities

The SOFC Program is flexible and can operate on both natural gas and syngas. The platform is also capable of producing both electricity and hydrogen. Therefore, the following recommendations continue to be critical aspects of the program:

Hydrogen Generation
The demand for sources of hydrogen is increasing due to increased demand for hydrogen in power generation. SOFCs, when operating in the reverse mode as an electrolyzer, produce hydrogen on demand, which eliminates the need to store large quantities of a combustible gas. The Program has begun efforts to develop SOFCs as efficient and cost-effective electrolyzers (also referred to as Solid Oxide Electrolysis Cells, or SOECs). These efforts should continue to expand as the demand for safe sources of hydrogen increases.

Figure 1. Implementation of SOFC Recommendations by DOE R&D Program

Activity	2018-2020	2021-2024	2025-2030
Industrial Engagement	Data sharing and scaling of commercial systems		
Validation and FEED Studies (Ongoing)	200 kWe Long-Term Testing 5,000 and up to 8,000 hours		
	FEED Study for 1MWE SOFC System		
Early-Stage Applied and Basic SOFC R&D on Coal Syngas for Electricity and Hydrogen Generation	Effects of High-Temperature Operations on Materials Degradation		
	Optimizing Systems Performance – Operating Lifetime Longevity		
	Simulation of Optimized SOFC Systems – Reducing Costs		
	Replacing Specialty Items and Materials (Supply chain R&D)		
SOFC Demonstrations			1+ MWe demonstration projects that meet DOE Goals

VII. Summary

Since the beginning of the SOFC Program in 1995, DOE has invested $750 million in the development of these power systems. These awards have enabled RD&D, culminating in two commercial-scale systems: a 200 kWe by FuelCell Energy currently in testing (shown below in Figures 1 and 2) and a 250-kWe system by LG Fuel Cell Systems, which has since departed the U.S. market. Throughout this effort, DOE-funded RD&D has identified gaps in state-of-the-art knowledge of SOFC power systems. Since 1995, under the direction and funding of the Program, work at the National Laboratories has established a technological foundation advancing the TRL of various SOFC components and processes to as high as TRL 6. The Program believes support of SOFC RD&D should continue, as this work will increase the commercialization of SOFC power systems and increase competition among the commercial entities.

DOE began funding research in SOFC technologies through National Laboratories, including Argonne National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, and National Energy Technology Laboratory. This R&D established bedrock fundamentals. As the research matured, by the end of 2015, DOE shifted the majority of its research to industry and university partners. The National Laboratories occasionally were in need of specialization to address unique issues within the key technology areas, and the most effective way to achieve that was to enlist the help of academic institutions and private companies with that special expertise. DOE should continue to engage with the private sector to further SOFC development.

Several challenges continue to face the development of SOFCs. The mix of available utility-scale generation technologies and their relative costs has made the advancement of SOFC technologies appear less commercially attractive than previously considered. Therefore, to foster SOFC innovation, the Program cannot rely solely upon the private sector, which will likely not risk the capital. An additional challenge is the varying levels of support for differing fuel sources from Congress and different administrations, which can create risks associated with long-term research investment.

There has been progress made in each of the technical areas for which DOE has set goals. These noteworthy achievements are real steps toward commercialization, and continued Federal funding is necessary to encourage private sector development. Significant advances, including prototype field-testing of 200 kW systems, have been since 2014.

VIII. Acronyms and Key Terms

Acronyms

BOP	balance of plant
DOE	U.S. Department of Energy
FAR	Federal Acquisition Regulations
FEED	front-end engineering design
FOA	funding opportunity announcement
FY	fiscal year
kW	kilowatt
kWe	kilowatt-electric
LG	LG Fuel Cell Systems, Inc.
LSCF	lanthanum strontium cobalt ferrite
MW	megawatt
MWe	megawatt-electric
R&D	research and development
RD&D	research, development, and demonstration
SME	subject matter expert
SOEC	Solid Oxide Electrolysis Cell
SOFC	solid oxide fuel cell
SOPO	Statement of Project Objectives
TRL	technical readiness level
YSZ	yttria stabilized zirconia

Key Terms

Annual Report – Federal Acquisition Regulations (FAR) require that award recipients submit a yearly report to the Department of Energy (DOE)

Anode – The negative electrode that releases electrons to the external circuit and oxidizes the fuel during the electrochemical reaction

Balance of Plant (BOP) – A term generally used in the context of power engineering to refer to all the supporting components and auxiliary systems of a power plant needed to deliver the energy, other than the generating unit itself

Cathode – The positive electrode that catalyzes the transfer of electrons from the external circuit and reduces air during the electrochemical reaction

Cell Development – The Key Technology Area that involves the components of the SOFC—the anode, cathode, and electrolyte

Core Technology – The Key Technology Area that involves interconnects and seals, identification and mitigation of stack-related degradation, development of computational tools and models, and laboratory- and bench-scale testing to improve the reliability, robustness, endurance, and cost of stacks and BOP components, respectively

Electrolyte – The medium that provides the ion transport mechanism between the cathode and anode of the cell

Final Report – FAR-required final technical report submitted to DOE at the conclusion of the award contract
Funding Opportunity Announcement – A document made available to the general public describing goals that DOE is looking achieve; Candidates submit a SOPO in order to compete for funding to help DOE achieve their stated goals
Getters —A deposit of reactive material that absorbs or reacts with select chemical species in the air removing them from the system
Interconnects —Components of the stack and fuel cell that connect the anode, cathode, and electrolyte to other BOP components
Quarterly Report – FAR-required report submitted to DOE four times/year
Reform —The chemical process of changing hydrocarbon fuels to hydrogen and carbon dioxide
Solid Oxide Fuel Cell– A power generation system comprised of an anode, cathode, and electrolyte. Feeding fuel and air to the system via BOP components generates power
Stack – Multiple individual fuel cells combined into a single unit in order to generate larger amounts of power than possible with a single fuel cell
Statement of Project Objectives– A document submitted in response to a FOA by a potential project performer describing the tasks and approach to complete goals established via the FOA
Systems Development – The Key Technology Area involving design and manufacture of fuel cells, integration of cells, hardware development, manufacturing process development, commercialization of technology, and market penetration